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Light transmission asymmetry and optical diode*

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Abstract. We have suggested and realized a giant asymmetry of the transmission of light propagating through a linear nonmagnetic optical system that consists of a nanohole in metal film deposited on the surface of a one-dimensional photonic crystal. The asymmetry of the light transmission is caused by two factors: (i) practical impossibility to reverse the wavefront of light passing through a nanohole whose diameter is much smaller than the wavelength of light; and (ii) increase of photonic crystal transmission at photonic bandgap wavelengths due to strong modification of k-vector of incident light caused by diffraction on a nanohole (optical "clearance" of the photonic crystal). We show that in such optical element it is possible to realize optical diode whose reverse transmission can be suppressed by a factor of more than 30 000.

1 Introduction

Basic research on nanooptics has opened the possibility of creating optical nanodevices that enable control of the propagation of light on the nanometer scale [1–9]. A separate class of nanodevices is formed by the so-called optical nanodiodes, which transmit light predominantly in a single direction and are characterized by strong optical nonreciprocity [10].

In classical electrodynamics, the terms reciprocity and nonreciprocity are used to describe the electromagnetic properties of physical systems that are related to the time reversal of local electric currents and the corresponding electromagnetic fields [11]. In 1856, Helmholtz introduced the notion of reciprocity in optics [12]. Later, Lorentz proved a theorem [13], according to which reciprocity can be violated only in the following three types of optical media: (i) magnetooptical media; (ii) nonlinear media; and (iii) media with time-dependent dielectric permittivity or time-dependent magnetic permeability [10]. The Lorentz reciprocity theorem is a basic lemma that is used to prove several theorems in electromagnetic systems [14].

According to electromagnetic theory, optical diodes can be produced only in those cases where the Lorentz reciprocity theorem is violated [10]. Recently, optically nonreciprocal nanodevices have been designed using media with magneto-optical properties [15–17], nonlinear media [18,19], and media with time-dependent optical properties [20,21].

However, there are optical systems that satisfy the Lorentz reciprocity theorem, but exhibit different transmission coefficients upon their illumination from opposite sides: the property of so-called *transmission asymmetry* [22–24]. This constitutes a different class of devices. The objective of this work is to present an optical element that exhibits a record high level asymmetry of optical transmittance and can be used as an *efficient* optical diode.

As a particular realization of this idea, we consider an optical system that consists of a metal film with a nanohole arranged on a one-dimensional photonic crystal. The system satisfies the conditions of the Lorentz reciprocity theorem. The unique feature of the system is a giant optical asymmetry, which is caused by two factors: (i) practical impossibility to reverse the wavefront of light passing through a nanohole whose diameter is much smaller than the wavelength of the light; and (ii) increasing of the photonic crystal transmission at photonic bandgap wavelengths, due to strong modification of k-vector of incident light caused by diffraction on a nanohole (optical "clearance" of the photonic crystal).

The "clearance" effect is the increase of light transmission at wavelengths corresponding to the photonic crystal band gap. This effect is well-known for the parallel light beams incident on the photonic crystal. In this case, a significant increase in light transmission at wavelengths of the photonic crystal band gap can be realized by changing the angle of incidence of the light beam [25]. In this case, changing the angle of incidence leads to violation of the destructive interference of light that forms a band gap of the photonic crystal. There is other known implementation of such "clearance" effect, using structural

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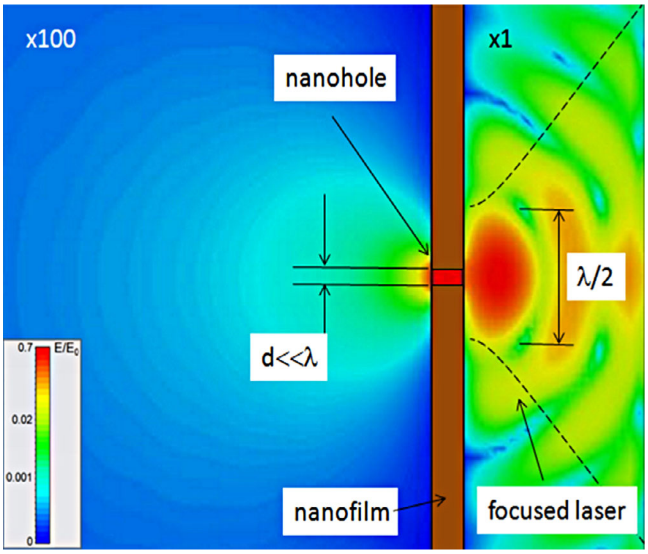

Fig. 1. The spatial distribution of the field amplitude of a tightly focused laser beam on a nanohole in a gold metallic film; the pattern of the light passing through the nanohole, calculated using the FDTD method (wavelength – 800 nm, diameter – 60 nm, film thickness – 200 nm). The amplitude of the field passing through the nanohole is scaled-up 100-fold.

disorder in photonic crystals that causes multiple scattering of light [26]. In this case, the light-scattering centers are deliberately introduced in a photonic crystal to break out the interference conditions that form a photonic crystal band gap. In the present study we use a different mechanism for violations of the interference – the diffraction of light on a single nanohole. Namely, the transmission of light through a single nanohole dramatically changes the wave vector of the light wave, which inevitably affects the spectral properties of the photonic crystal band gap.

2 Optical diode based on a single nanohole

The key element, of the optical system that we consider in this work, is a single nanohole made in metal film. As is well known, the nanohole makes it possible to create a nanolocalized light source that is free from background illumination [27]. The creation of nanolocalized light sources is extremely important challenge for applications in nanooptics [28].

Figure 1 presents the calculated distribution of the field amplitude of laser radiation, focused into a diffraction-limited spot on a nanohole with a diameter 60 nm made in a 200 nm thick gold film. The calculation was performed using the finite-difference time-domain (FDTD) method. It is seen from Figure 1 that the radiation field passing through the nanohole is localized near the nanohole itself. The dimension of the field localization is roughly equal to the diameter of the nanohole. The radiation from the nanohole in the far-field zone is characterized by a wide range of directions of wave vectors, which lie within a solid angle of 2π steradians [29]. In addition, the nanohole is a source of plasmonic waves that propagate along the metal nanofilm-air interface [30].

Let us consider the properties of the optical system presented in Figure 1. According to the Lorentz theorem, this optical system is reciprocal, since it does not possess any of the three above-listed properties that rule out nonreciprocity. In the rigorous electromagnetic theory, the property of reciprocity is related to time reversal of the wavefront of the transmitted radiation. In the system presented in Figure 1, this means that it is necessary to reverse the wavefront of the light field that passes through the nanohole. In addition, it is necessary to realize the plasmonic waves reversal excited on the film surface. In practice, it does not seem possible to solve this problem.

The figure of merit of the optical nanodiode, based on use of the nanohole, originates from the following physical considerations. The minimum diameter of the spot of the focused radiation is restricted by the diffraction limit, and is given by, $D_{\min} \simeq \lambda/2$, where λ is the wavelength of the light. If the diameter of the nanohole is substantially less than the light wavelength, $d \ll \lambda$, the measure of the possible optical asymmetry can be estimated as a ratio of the area of the focused laser spot to the area of the nanohole. This ratio is given by, $\zeta \simeq D_{\min}^2/d^2 = \lambda^2/4d^2$. At $\lambda = 780$ nm and $d = 60$ nm, the degree ζ is found to be, $\zeta \simeq 42$.

Nevertheless, a nanohole cannot be used as an optical diode, because the transmission of light from both sides of the screen with a nanohole is the same. To break the symmetry of light transmission we have added a planar photonic crystal from one side of metal screen with a nanohole.

Figures 2a and 2b show the schematic of an optical diode, based on a nanohole that is investigated in this work, and which demonstrates optical asymmetry. The device consists of a gold film with a through-hole and a photonic crystal. The addition of the photonic crystal to the film with a nanohole leads to the asymmetrical transmission of light, with the wavelength within a spectral bandgap of the photonic crystal: the photonic crystal blocks the transmittance of light; only light that is emitted from the nanohole can pass through the photonic crystal due to photonic crystal "clearance" effect.

The optical diode design needs to satisfy the following. On the one hand, the film should be thick enough, in order to prevent the incident light on the film outside of the nanohole from passing through the film; on the other hand, the film should be thin enough to ensure significant transmission of light through the nanohole. The diameter of the nanohole is chosen to be much smaller than the wavelength of light. To realize a substantial "clearance" effect of a photonic crystal the spectral bandgap of the photonic crystal should have sharp edges.

3 Experimental setup and samples

We created an optical diode using two optical elements: (1) a photonic crystal; and (2) a metal film with a nanohole. The parameters of the photonic crystal were

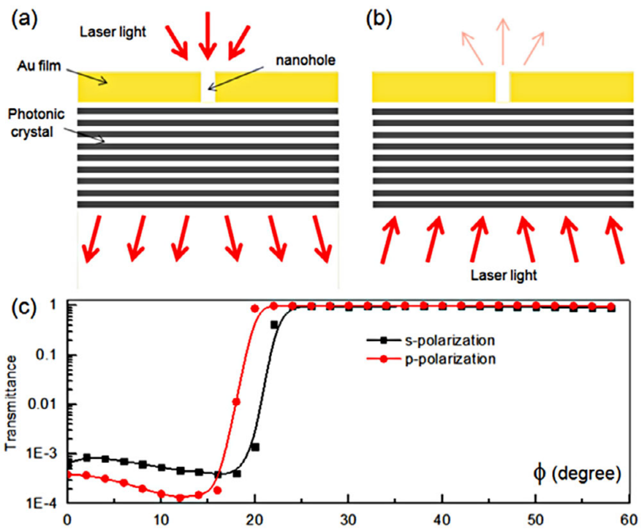

Fig. 2. Schematic of an optical diode based on a metal film with a nanohole and a photonic crystal: (a) forward light transmission and (b) reverse transmission. (c) Measured transmittance of the photonic crystal illuminated by a plane wave of the laser radiation with a wavelength of 783 nm at different angles of incidence ϕ.

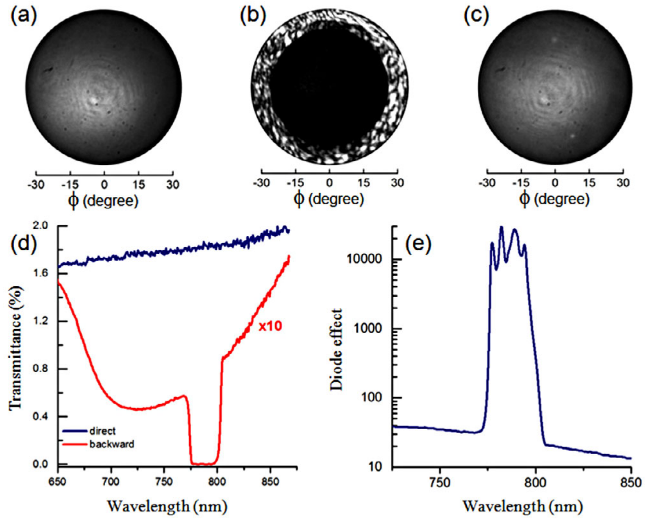

Fig. 3. Light intensity distribution in the focal plane of an objective upon illumination of an experimental sample in the forward direction by laser radiation at different wavelengths: (a) 760 nm, (b) 783 nm and (c) 840 nm. Measurements of the optical diode efficiency: (d) the spectral transmissions of the sample in the forward and reverse directions and (e) the ratio of the spectral transmissions of the sample in the forward and reverse directions (optical diode effect).

as follows. The band gap of the photonic crystal was centered at a wavelength of 783 nm, with spectral width of 20 nm and characterized by sharp edges of spectral transmittance (NOTCH filter, Thorlabs Inc.). The 200 nm thick metal film, was prepared by thermal evaporation of gold on the surface of an ultrathin 40 nm thick silicon oxide membrane [31]. Using a tightly focused beam of Ga ions, 10×10 arrays of 120 nm diameter nanoholes with 4 μm spacing between them were produced. By varying the diameter of the focused laser beam, between 1.5 and 50 μm, the chosen spacing between nanoholes made it possible to illuminate either the entire matrix with the nanoholes or each individual nanohole.

The optical diode operates as follows. If the incident radiation on the optical diode falls on the photonic crystal as shown in Figure 2b (which corresponds to the case of the backward transmission, i.e., reverse, in terms of the electrical diode), the radiation is significantly attenuated, because of the reflection from the photonic crystal. Further, the presence of a large number of layers of the photonic crystal leads to a significant increase in the diameter of the focused radiation, resulting in an increase in the degree ζ. If the incident radiation falls on the nanofilm (Fig. 2a, the case of the forward transmission), then the light passing through the nanohole propagates through a large solid angle on the order of 2π steradians. A major part of this radiation propagating at large angles with respect to the normal to the photonic crystal, passes without significant attenuation due to the photonic crystal "clearance" effect.

The characteristics of the optical asymmetry were measured, using a Nikon Eclipse Ti/U inverted microscope that was equipped with a spectrometer and a CCD camera. A Bertrand lens, installed in the microscope, projects the back focal plane of the objective onto the CCD camera, which makes it possible to measure the angular distribution of the light passing through the sample [32]. We used a broadband supercontinuum source (RnD ISAN) and a tunable Ti:Sapphire CW laser (Avesta, Inc.) as the radiation sources.

4 Results

Figure 2c shows the results of measurements of the passage of the laser radiation with a wavelength of 780 nm, through the photonic crystal (without the gold nanofilm) at different incidence angles. The chosen wavelength of the laser radiation corresponds to the center of the bandgap of the photonic crystal. As can be seen in the figure, for incidence angles between 0° and 18° to the normal incidence on the photonic crystal, the radiation is attenuated by a factor of $5 \times 10^3 \div 10^4$. For angles of incidence greater than about 18°, the transmission coefficient of the photonic crystal is significantly increased due to an increase in the propagation path of light in all layers of the photonic crystal. As a result, the conditions of the radiation constructive interference in the photonic crystal, which forms its bandgap, are violated (the optical "clearance" effect of the photonic crystal).

Figures 3a–3c show the results of measurements of the angular distribution of laser radiation passing through the sample, consisting of a metal film with a single nanohole and a photonic crystal. The laser radiation was focused onto the single nanohole into a spot with a diameter 1.5 μm. In these measurements, we have used the laser radiation at different wavelengths: (i) $\lambda = 783$ nm (wavelength that corresponds to the center of the band gap of the photonic crystal) (Fig. 3b); (ii) $\lambda = 760$ nm (wavelengths that are shorter than the wavelength of the center of band gap of the photonic crystal) (Fig. 3a); and (iii) $\lambda = 840$ nm (wavelengths that are longer than the wavelength of the center of bandgap of the photonic crystal) (Fig. 3c). The maximum value of the measured angle, which is 36.8°, is restricted by the numerical aperture (NA = 0.6) of the microscope objective used. As can be seen in Figure 3c, a dip in the transmission pattern is observed between 0° and 18°, for $\lambda = 783$ nm, corresponding to the center of the bandgap of the photonic crystal. A halo appearing around this dip is a result of optical "clearance" of the photonic crystal for large angles of the incident light.

In a separate experiment, we measured the increase in the size of the focal spot of the tightly focused laser beam that results from the passage of the beam through the photonic crystal. In these measurements, we used laser radiation of 780 nm wavelength, which was focused by a microscope objective with a numerical aperture of NA = 0.6, and a focal length of $F = 6$ mm. The measurements showed that, in air, the laser radiation is focused onto a spot with a diameter of 1.5 μm. If the photonic crystal is placed behind the objective, the minimum size of the spot that we succeeded to achieve was 20 μm. Therefore, the minimum size of the focal spot significantly exceeds the value determined by the diffraction limit, and our estimates show that, taking into account the change in the diameter of the focal spot, the expected value of the degree of optical asymmetry should be as high as $\zeta = 50\,000$.

Figure 3d shows the results of measurements of the transmission spectrum of the examined optical diode, consisting of a metal film with a single nanohole and a photonic crystal (Fig. 2a), in the forward and reverse directions (for details of spectral measurements of light transmission through a single nanohole see [33]). These measurements were performed using broadband light (supercontinuum), which was focused onto the optical diode by an objective lens with NA = 0.6. The radiation passing through the optical diode was registered using an identical objective. As can be seen in the figure, the transmission spectrum is characterized by a bandgap with the center at a wavelength of 783 nm. The curves shown in Figure 3d were used to calculate the spectral dependence of light transmission asymmetry of optical diode, as shown in Figure 3e. As can be seen in the figure, at wavelengths where there is maximum attenuation of the photonic crystal, the degree of light transmission asymmetry attains a value of about 30 000. This is close to the expected value presented above.

The obtained value, of the degree of light transmission asymmetry, significantly exceeds the values that were found previously in nanosystems based on the magnetooptical effects [15], the use of nonlinear properties [18], and also in optical nanosystems in which the transmission asymmetry was demonstrated [24].

5 Conclusion

We have suggested and realized the occurrence of a giant asymmetry of the transmittance of light propagating through a linear nonmagnetic optical system that consists of a nanohole in metal film deposited on the surface of a one-dimensional photonic crystal. The asymmetry of the light transmittance is caused by two factors: (i) practical impossibility to reverse the wavefront of light passing through a nanohole whose diameter is much smaller than the wavelength of the light; and (ii) increase of photonic crystal transmission at photonic bandgap wavelengths due to strong modification of k-vector of incident light caused by diffraction on a nanohole.

We show experimentally that in such optical element it is possible to realize optical diode whose reverse transmission can be suppressed by a factor of more than 30 000. We believe that further optimization of the geometry may yield even stronger asymmetry, with the transmission coefficient being rather large. We would like to emphasize that technologically, the proposed optical system has a simple structure and consists of the linear optical materials of photonic crystal and the metal film with nanoholes. This system appears to be much simpler and more effective than developed before [23].

As is well known, the practical use of all optical nanodevices, based on a nanohole prepared in a metal film, is limited by low levels of the transmission of light through the nanohole (for example, in the presented work, the light transmittance through a single nanohole was about 1.9%). In this connection, we note that, there is a practical possibility to significantly increase the transmission of light through the nanohole, by using the optical Tamm state [34]. Thus, it was shown in [33] that, with this method, the transmission through a single nanohole can be increased to 41%.

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Author contribution statement

P.N.M. proposed the main idea of the paper, designed and performed the measurements, analyzed the data and wrote the paper; A.E.A. performed the computer simulations and photonic crystal spectral characterization; A.S.K. prepared the samples, performed spectral measurements of the samples; V.I.B. supervised the project, analyzed the data and wrote the paper. All authors were involved at all stages of preparation of the manuscript.

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